Indian J Phys **80** (7), 697-701 (2006)

IJP

Cosmic ray intensity variations associated with sunspot numbers and tilt angle

Meera Gupta, V K Mishra and A P Mishra*

Department of Physics, A P S University, Rewa-486 003, Madhya Pradesh, India

E-mail apm_apsu@yahoo co in

Received 19 December 2005, accepted 12 May 2006

We have performed a correlative analysis to study the relationship of sunspot numbers (SSN) and tilt angle with cosmic ray intensity (CRI) observed by the neutron monitor stations having different cut-off rigidity for the period 1976 to 2005 covering solar cycles 21, 22 and 23 It is found that tilt angle and sunspot numbers are positively correlated with each other and have inverse correlation with cosmic ray intensity The time-lag analysis has been performed by the method of 'minimizing correlation coefficient' and it is found that time-lag is larger for odd solar cycles and smaller for even solar cycles We have also calculated 'running cross correlation coefficient' between cosmic ray intensity and tilt angle and observed that the correlation is positive during the maxima of odd cycles 21 and 23 The 22-year variational pattern is clearly apparent in the different types of analysis based on tilt angle observations it has been noticed that the behaviour of cycle 23 in declining phase is different than of cycle 21 and 22

Keywords Cosmic ray intensity, sunspot numbers, tilt angle

PACS Nos. 96 50 S-, 96 60 qd, 96 50 Xy

1. Introduction

The intensity of galactic cosmic rays varies inversely with sunspot numbers having their maximum intensity at the minimum of the 11-year sunspot cycle [1,2] The cosmic ray intensity (CRI) curve also appears to follow a 22-year cycle with alternate maxima being flat-topped and peaked as predicted by models of cosmic ray modulation based on the observed reversal of the Sun's magnetic field polarity after every 11-year and curvature and gradient drifts in the large-scale magnetic field of the heliosphere [3–5]

Recently, features of the interplanetary medium have been explained on the basis of heliospheric neutral current sheet (HCS), which separates the whole heliosphere into the two regions of opposite polarity of magnetic field In each hemisphere, the field is well approximated by a Parker Archimedian spiral with the sense of the field being outward in one hemisphere and inward in the other The field direction in each hemisphere altered in each 11-year sunspot cycle At the solar minimum, the current sheet is nearly equatorial with the northern hemisphere, solar magnetic field being in one direction and the southern magnetic field having the opposite sign The solar magnetic field structure near the sunspot maxima is complex, where it corresponds roughly to increasing the inclination of the current sheet The inclinations of the heliosphere neutral current sheet along the equatorial plane of heliosphere are often named as tilt angle. The waviness of neutral current sheet *i e.* tilt angle has been used as solar/interplanetary index by various investigators to explain the long-term modulation of cosmic rays [6–8] The tilt angle (α) is computed by averaging the maximum latitude through the neutral line in the north and south hemisphere in each Carrington rotation. The heliospheric neutral current sheet and its waviness provide us some basic physical mechanism to explain the long-term modulation of galactic cosmic rays

2. Data and method of analysis

In this work, we have taken waviness of heliospheric neutral current sheet (HCS) or tilt angle as a key parameter

*Corresponding Author

in drift model of modulation and the cosmic ray intensity for the period of 1976 to 2005. To study the average behaviour of cosmic ray intensity, monthly mean values of neutron monitor stations of different cut-off rigidity (Oulu, Kiel and Huancayo) have been used, whereas the values of tilt angle were obtained from the Wilcox solar observatory (WSO, classical model).

The cross correlation coefficient (r) between cosmic ray intensity and tilt angle with time-lag has been calculated for the different solar cycles (21, 22 and 23) using the method of 'minimizing correlation coefficient'. Here, we have selected both the series CRI and tilt angle for the same period with zero time-lag and then shifted one series by a step of one month and calculated the cross correlation coefficient between both the series. Similarly, the other series has also been shifted by one month and the new value of cross correlation coefficient is calculated. As such, the time (number of shifted months) is obtained, when the anti-correlation coefficient is maximum. This is the time-lag between both the series CRI and tilt angle. The probable error for each value of correlation coefficient has been calculated by the formula. $PE = 0.6745\ (1 - r^2)/\Delta N$, where r is the correlation coefficient and N is the size of sample (data points).

In the present paper, 'running cross correlation method' has been used to study the relationship between CRI and solar activity indices [9,10]. In the said method, we use a time window of width T centered at time $t \cdot [t - T/2,\ t + T/2]$. The cross correlation coefficient $c(t)$ is calculated for data within this window. Then the window is shifted in time by a small time step $\Delta t < T$ and the new value of the cross correlation coefficient is calculated. Here, we have used the time shifting of one month to calculate the correlation coefficient for each month between CRI-SSN (sunspot numbers) and for CRI-tilt angle for the period 1976 to 2005. The time window has been taken of 50-months. This value was chosen to match two contradictory requirements · (i) uncertainty of the calculated $c(t)$ are smaller for large T and (ii) T should be small in order to reveal fine temporal structure of the cross correlation function.

3. Results and discussion

The relationships of sunspot numbers and tilt angle to cosmic ray intensity have been studied earlier [11,12]. The inverse correlation between tilt angle and cosmic ray intensity along with 22-year patterns is observed in evolution of tilt angle. Here, an attempt has been made to extend the study for recent period to establish the relationship of sunspot numbers and tilt angle to cosmic ray intensity considering low (Oulu, $Rc \sim 1$ GV), middle (Kiel, $Rc \sim 3$ GV) and high (Huancayo, $Rc \sim 13$ GV) cut-off rigidity neutron monitor stations using different method of analysis for the period 1976 to 2005 (solar cycle 21, 22 and 23).

To see the associative behaviour of different cut-off rigidity neutron monitor stations with tilt angle, we have used the % of monthly mean value of CRI for Oulu ($Rc \sim 1$ GV), Kiel ($Rc \sim 3$ GV) and Huancayo ($Rc \sim 13$GV) from 1976 to 2005. Figure 1 shows overall inverse correlation between tilt angle and % CRI (100% normalized at May 1965) of all the three stations during the whole period of investigation. Looking the similar behaviour of low to high cut-off rigidity stations, we have chosen the monthly mean value of Kiel ($Rc \sim 3$ GV) a middle cut-off rigidity neutron monitor station. The variation of CRI (Kiel) and tilt angle along with sunspot numbers from 1976 to 2005 is shown in Figure 2. The sunspot number and tilt angle is showing

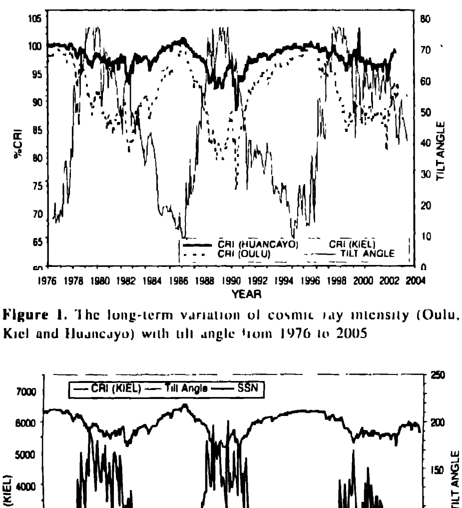

Figure 1. The long-term variation of cosmic ray intensity (Oulu, Kiel and Huancayo) with tilt angle from 1976 to 2005.

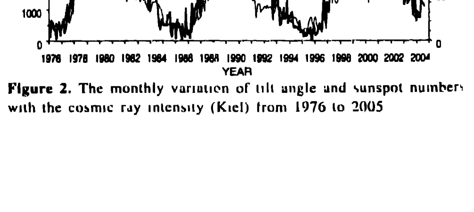

Figure 2. The monthly variation of tilt angle and sunspot numbers with the cosmic ray intensity (Kiel) from 1976 to 2005.

similar pattern and positively correlated with each other, whereas cosmic ray intensity is inversely correlated with tilt angle as well as with sunspot numbers with some period time-lag during the whole period of investigation. The average correlation coefficient between CRI and SSN for the solar cycles 21, 22 and 23 is ~ –0.614, –0.906, and –0.619, respectively. The correlation between CRI and tilt angle is ~ –0.571, –0.911 and –0.614 for the solar cycles 21, 22 and 23, respectively. Now, we have calculated the cross correlation coefficient between CRI and tilt angle by shifting of both the series one by one by a step of one month. The cross correlation coefficient factor with different time-lag and statistical error bars for solar cycles 21, 22 and 23 are shown in Figure 3. It is observed that during odd cycles 21 and 23, the time-lag between CRI

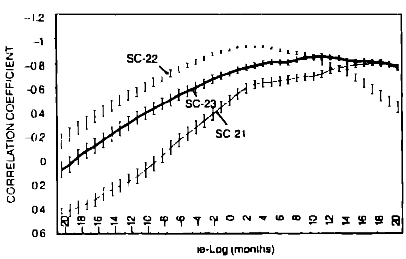

Figure 3. The cross correlation coefficient factor between cosmic ray intensity (Kiel) and tilt angle with different time-lags and statistical error bars for solar cycles 21, 22 and 23

and tilt angle is ~17 and 11–months at the time of maximum anti-correlation coefficient ($c(t)$ ~ –0.8) whereas for even cycle 22, the time-lag has been found to be ~2-months at the time of maximum anti-correlation coefficient ($c(t)$ ~ –0.9). It is also found that the time-lag is ~12 and 10-months for odd solar cycles 21 and 23 and ~4-months for even solar cycle 22 in the case of CRI and SSN. The time-lag between CRI-tilt angle and CRI-SSN is larger for odd solar cycles and smaller for even solar cycles, which supports the even-odd asymmetry of CRI cycles. Now, we have calculated the running cross correlation between CRI-tilt angle and also for CRI-SSN for the whole period of study (Figure 4). This type of analysis is necessary to explain the momentary behavior of cross correlation function with respect to time, the value of correlation coefficient is different for the different phases of same solar cycle and it changes with time. The values obtained by this method if averaged over a cycle, will represent the correlation coefficient for particular cycle.

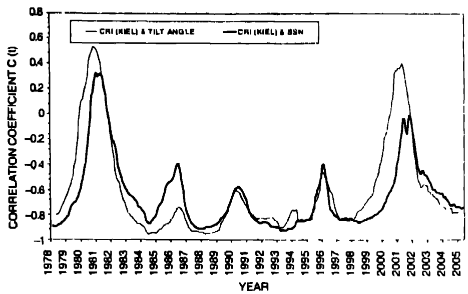

Figure 4 The running cross correlation coefficient factor $c(t)$ between cosmic ray intensity (Kiel) and sunspot numbers as well as between cosmic ray intensity (Kiel) and tilt angle from 1976 to 2005

One can see that the correlation is stronger during ascending and descending phases and it is weaker during the maxima and minima of the solar cycles. It is evident that there is 5.5-year periodicity in the observed peaks occurred which is half of the (11-year) solar cycle period. It is also observed that running cross correlation function $c(t)$ is positive during the maxima of odd cycle 21 and 23 for both the cases *i.e* for CRI-SSN and CRI-tilt angle. However, the value of cross correlation coefficient is almost similar in the case of CRI-tilt angle relationship (~ 0.6) for the maxima of both the cycles 21 and 23 and it is different in the case of CRI-SSN, which is ~0.3 and ~0.08 for the maxima of the cycles 21 and 23, respectively.

This shows the 22-year variational pattern of cosmic ray intensity and supports the odd-even hypothesis of the CRI cycles. The differences observed in the relationship between CRI-SSN and CRI-tilt angle are perhaps attributable due to the different sunspot activity in solar cycles 21 and 23, which is also clear from Figure 2. The tilt angle behaviour is similar during the rising phases of the solar cycles 21, 22 and 23 and different during the declining phase of the solar cycle 23 than the solar cycles 21 and 22 (Figure 2). The similarities in the tilt angle evolution during the rising of cycles 21 and 22, have also been reported [12–14].

In the drift formulation of cosmic-ray modulation [3,15], positively charged cosmic rays preferentially enter the heliosphere from the direction of the solar poles during $qA > 0$ cycles (corresponding to times when the polarity of the solar magnetic field is outward in the northern hemisphere) such as ~1970–1980 and ~1990–2000. During $qA < 0$ periods such as ~1980–1990 when the solar field polarity is reversed, cosmic rays (positively charged) approach the Sun from along the HCS During $qA >.0$ times, it might be expected that incoming cosmic rays will be less affected by drift effects associated with an increase in the tilt angle at the beginning of a solar cycle (odd-numbered) or by diffusion associated with enhanced coronal mass ejection (CME) activity CMEs, which are thought to be a key element in diffusion/convection-based pictures of modulation [16], are characteristically confined to the Sun's equatorial regions early in the solar cycle and appear at higher latitudes during the course of the cycle as the streamer belt at the base of the HCS, moves pole ward At the beginning of even-numbered cycles ($qA < 0$), when cosmic rays approach the Sun along the HCS, they will be more readily affected by changes in the tilt angle and low-latitude CMEs Thus, the difference in the responsiveness to solar activity changes at the onset of even- and odd-numbered solar cycles, is consistent with a drift effect [5]

While the tilt angle increase was remarkably similar during the rising phase of the last three cycles (Figure 2), there is evidence that HCS evolution may differ on the decline of even- and odd-numbered solar cycles Specifically, the tilt angle appears to collapse to low angles more rapidly during the decline of even-numbered cycles such as 22 (peak in ~1990) We conclude that the differences observed in the relationship between CRI-SSN and CRI-tilt angle may be due to the low activity of the solar cycles 23

Galactic cosmic rays after entering into heliosphere (the region of space extending upto more than 100 AU, dominated by the solar wind), must overcome the outward flowing solar wind This solar wind prevents the lowest energy of galactic cosmic rays from reaching the earth Resultantly, the galactic cosmic rays are modulated by the solar outputs depending on the level of solar activity and their short term and long term variability (11-year activity cycle) The Sun possesses well-known 11-year sunspot cycle, which is reflected through the variability of plasma and field as well as modulation of cosmic rays. The galactic cosmic ray intensity internally observed at earth is anti-correlated with the level of solar activity *i e* during high solar activity (large number of sunspots) the cosmic ray intensity is observed to be low and *vice-versa*. It is also observed that the anti-correlation between solar activity parameters and cosmic ray intensity is strong during ascending and descending phases of solar cycle, whereas it becomes weaker (lower) during extrema (maxima and minima). This is because of very small variations in either of the indices (solar parameters or CRI) during maxima and minima in comparison to ascending and descending phases of the solar cycle [17]

Moreover, the penetration of cosmic rays into the heliosphere is also affected by the structure of the solar magnetic field, which is clearly evident through the 22-year magnetic cycle of the Sun (based on the concept of solar magnetic field reversal after 11-year) Consequently, the two successive cosmic ray cycles differ significantly in their length and variational characteristics [18,19]

The solar modulation mechanism of galactic cosmic rays is still based on the standard model of diffusion, convection and adiabatic deceleration effect, where the interplanetary magnetic field lines including drift processes determine the path of individual particles through the heliosphere This leads to characteristic differences between adjacent solar cycles due to the different polarity of the solar and large-scale interplanetary magnetic fields Since the polarity of the solar magnetic field reverses sign about every 11-year near the time of maximum solar activity, thus successive solar activity maxima are characterized by different solar field polarity Such a study gives us a clue to access the nature of cosmic ray variability in relation to odd-even hypothesis on the basis of 11-year solar activity and 22-year magnetic cycles However, for a better understanding of odd-even cycle's differences, the influences of curvature of interplanetary magnetic field on the transport of cosmic ray should also be considered

Acknowledgment

The authors thank the anonymous referees for their valuable comments for the improvement of this paper.

References

[1] S E Forbush *J Geophys Res* **59** 525 (1954)
[2] S L Forbush *J Geophys Res* **63** 651 (1958)
[3] J R Jokipii E H Levy and W B Hubbard *Astrophys J* **213** 861 (1977)
[4] J R Jokipii and B Thomas *Astrophys J* **243** 1115 (1981)
[5] E J Smith *J Geophys Res* **95** 731 (1990)
[6] W R Webber and J A Lockwood *J Geophys Res* **93(A8)** 8735 (1988)
[7] D B Swinson and S I Yasue *J Geophys Res* **97** 19149 (1992)
[8] H S Ahaluwalia *Planet Space Sci* **40** 1227 (1992)

[9] I G Usoskin, H Kanane, K Mursula, P Tankanen and G A Kavaltsor *J Geophys. Res* **103(A5)** 9567 (1998)

[10] V K Mishra and D P Tiwari *Indian J Radio Space Phys* **32** 65 (2003)

[11] E W Cliver, V Boriakoff and K H Bounar *J Geophys Res* **101** 27091 (1996)

[12] E W Cliver and A G Ling *Astrophys J* **551** 189 (2001)

[13] S T Suess, D J McComas and J T Hocksema *Geophys Res Lett* **20** 161 (1993)

[14] E W Cliver *J Geophys Res* **98** 17435 (1993)

[15] M S Potgieter *Space Sci Rev* **83** 147 (1998)

[16] L F Burlaga, F B McDonald, N F Ness, R Schwenn, A J Lazarus and F Mariani *J Geophys Res* **89** 6579 (1984)

[17] H S Ahaluwalia and M D Wilson *J Geophys Res* **101** 4879 (1996)

[18] H S Ahaluwalia *J Geophys Res* **99** 11561 (1994)

[19] R P Kane *Indian J Radio Space Phys* **34** 299 (2005)